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Chapter 3

Engineering materials and their properties

3.1 Introduction and synopsis

Materials, one might say, are the food of design. This chapter presents the menu: the full shopping list of materials. A successful product — one that performs well, is good value for money and gives pleasure to the user — uses the best materials for the job, and fully exploits their potential and characteristics: brings out their flavour, so to speak.

The classes of materials — metals, polymers, ceramics, and so forth — are introduced in Section 3.2. But it is not, in the end, a material that we seek; it is a certain profile of properties. The properties important in thermo-mechanical design are defined briefly in Section 3.3. The reader confident in the definitions of moduli, strengths, damping capacities, thermal conductivities and the like may wish to skip this, using it for reference, when needed, for the precise meaning and units of the data in the selection charts which come later. The chapter ends, in the usual way, with a summary.

3.2 The classes of engineering material

It is conventional to classify the materials of engineering into the six broad classes shown in Figure 3.1: metals, polymers, elastomers, ceramics, glasses and composites. The members of a class have features in common: similar properties, similar processing routes, and, often, similar applications.

Metals have relatively high moduli. They can be made strong by alloying and by mechanical and heat treatment, but they remain ductile, allowing them to be formed by deformation processes. Certain high-strength alloys (spring steel, for instance) have ductilities as low as 2%, but even this is enough to ensure that the material yields before it fractures and that fracture, when it occurs, is of a tough, ductile type. Partly because of their ductility, metals are prey to fatigue and of all the classes of material, they are the least resistant to corrosion.

Ceramics and *glasses,* too, have high moduli, but, unlike metals, they are brittle. Their 'strength' in tension means the brittle fracture strength; in compression it is the brittle crushing strength, which is about 15 times larger. And because ceramics have no ductility, they have a low tolerance for stress concentrations (like holes or cracks) or for high contact stresses (at clamping points, for instance). Ductile materials accommodate stress concentrations by deforming in a way which redistributes the load more evenly; and because of this, they can be used under static loads within a small margin of their yield strength. Ceramics and glasses cannot. Brittle materials always have

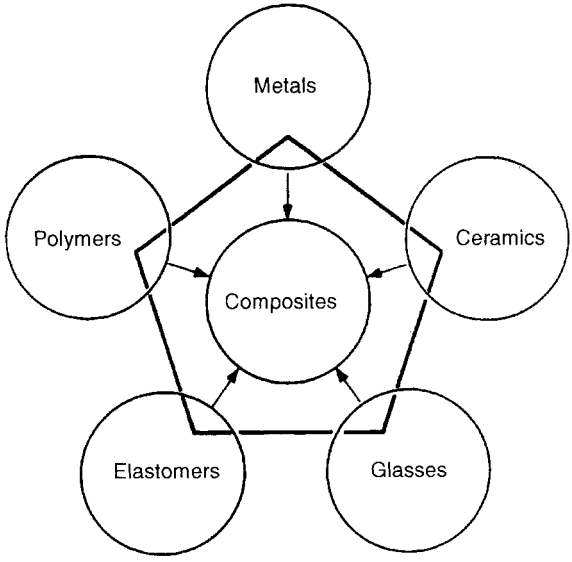

Fig. 3.1 The menu of engineering materials.

a wide scatter in strength and the strength itself depends on the volume of material under load and the time for which it is applied. So ceramics are not as easy to design with as metals. Despite this, they have attractive features. They are stiff, hard and abrasion-resistant (hence their use for bearings and cutting tools); they retain their strength to high temperatures; and they resist corrosion well. They must be considered as an important class of engineering material.

Polymers and *elastomers* are at the other end of the spectrum. They have moduli which are low, roughly 50 times less than those of metals, but they can be strong — nearly as strong as metals. A consequence of this is that elastic deflections can be large. They creep, even at room temperature, meaning that a polymer component under load may, with time, acquire a permanent set. And their properties depend on temperature so that a polymer which is tough and flexible at 20°C may be brittle at the 4°C of a household refrigerator, yet creep rapidly at the 100°C of boiling water. None have useful strength above 200°C. If these aspects are allowed for in the design, the advantages of polymers can be exploited. And there are many. When combinations of properties, such as strength-per-unit-weight, are important, polymers are as good as metals. They are easy to shape: complicated parts performing several functions can be moulded from a polymer in a single operation. The large elastic deflections allow the design of polymer components which snap together, making assembly fast and cheap. And by accurately sizing the mould and pre-colouring the polymer, no finishing operations are needed. Polymers are corrosion resistant, and they have low coefficients of friction. Good design exploits these properties.

Composites combine the attractive properties of the other classes of materials while avoiding some of their drawbacks. They are light, stiff and strong, and they can be tough. Most of the composites at present available to the engineer have a polymer matrix — epoxy or polyester, usually — reinforced by fibres of glass, carbon or Kevlar. They cannot be used above 250°C because the polymer matrix softens, but at room temperature their performance can be outstanding. Composite components are expensive and they are relatively difficult to form and join. So despite their attractive properties the designer will use them only when the added performance justifies the added cost.

The classification of Figure 3.1 has the merit of grouping together materials which have some commonalty in properties, processing and use. But it has its dangers, notably those of specialization (the metallurgist who knows nothing of polymers) and of conservative thinking ('we shall use steel because we have always used steel'). In later chapters we examine the engineering properties of materials from a different perspective, comparing properties across all classes of material. It is the first step in developing the freedom of thinking that the designer needs.

3.3 The definitions of material properties

Each material can be thought of as having a set of attributes: its properties. It is not a material, *per se*, that the designer seeks; it is a specific combination of these attributes: a *property-profile*. The material name is the identifier for a particular property-profile.

The properties themselves are standard: density, modulus, strength, toughness, thermal conductivity, and so on (Table 3.1). For completeness and precision, they are defined, with their limits, in this section. It makes tedious reading. If you think you know how properties are defined, you might jump to Section 3.4, returning to this section only if the need arises.

The *density*, ρ (units: kg/m^3), is the weight per unit volume. We measure it today as Archimedes did: by weighing in air and in a fluid of known density.

The *elastic modulus* (units: GPa or GN/m^2) is defined as 'the slope of the linear-elastic part of the stress–strain curve' (Figure 3.2). Young's modulus, E, describes tension or compression, the shear modulus G describes shear loading and the bulk modulus K describes the effect of hydrostatic pressure. Poisson's ratio, ν, is dimensionless: it is the negative of the ratio of the lateral strain to the

Table 3.1 Design-limiting material properties and their usual SI units*

Class	*Property*	*Symbol and units*	
General	Cost	C_m	(\$/kg)
	Density	ρ	(kg/m^3)
Mechanical	Elastic moduli (Young's, shear, bulk)	E, G, K	(GPa)
	Strength (yield, ultimate, fracture)	σ_f	(MPa)
	Toughness	G_c	(kJ/m^2)
	Fracture toughness	K_{Ic}	(MPa m$^{1/2}$)
	Damping capacity	η	(—)
	Fatigue endurance limit	σ_e	(MPa)
Thermal	Thermal conductivity	λ	(W/mK)
	Thermal diffusivity	a	(m^2/s)
	Specific heat	C_p	(J/kg K)
	Melting point	T_m	(K)
	Glass temperature	T_g	(K)
	Thermal expansion coefficient	α	(°K^{-1})
	Thermal shock resistance	ΔT	(°K)
	Creep resistance	-	(—)
Wear	Archard wear constant	k_A	(MPa^{-1})
Corrosion/ Oxidation	Corrosion rate	K	(mm/year)
	Parabolic rate constant	k_P	(m^2/s)

*Conversion factors to imperial and cgs units appear inside the back and front covers of this book.

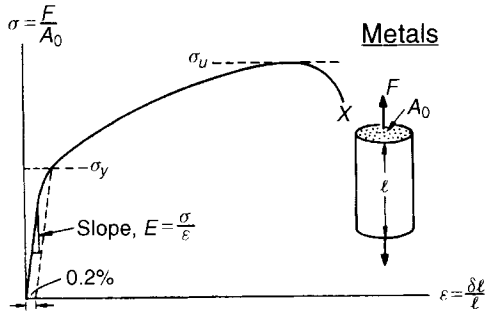

Fig. 3.2 The stress–strain curve for a metal, showing the modulus, E, the 0.2% yield strength, σ_y, and the ultimate strength σ_u.

axial strain, $\varepsilon_2/\varepsilon_1$, in axial loading. In reality, moduli measured as slopes of stress–strain curves are inaccurate (often low by a factor of two or more), because of contributions to the strain from anelasticity, creep and other factors. Accurate moduli are measured dynamically: by exciting the natural vibrations of a beam or wire, or by measuring the velocity of sound waves in the material. In an isotropic material, the moduli are related in the following ways:

$$E = \frac{3G}{1 + G/3K} \qquad G = \frac{E}{2(1+\nu)} \qquad K = \frac{E}{3(1-2\nu)} \tag{3.1}$$

Commonly $\nu \approx 1/3$

when $G \approx 3/8E$ (3.2a)

and $K \approx E$

Elastomers are exceptional. For these:

$\nu \approx 1/2$

when $G \approx 1/3E$ (3.2b)

and $K \gg E$

Data books and databases like those described in Chapter 13 list values for all four moduli. In this book we examine data for E; approximate values for the others can be derived from equations (3.2) when needed.

The *strength*, σ_f, of a solid (units: MPa or MN/m^2) requires careful definition. For metals, we identify σ_f with the 0.2% offset yield strength σ_y (Figure 3.2), that is, the stress at which the stress–strain curve for axial loading deviates by a strain of 0.2% from the linear-elastic line. In metals it is the stress at which dislocations first move large distances, and is the same in tension and compression. For polymers, σ_f is identified as the stress σ_y at which the stress–strain curve becomes markedly non-linear: typically, a strain of 1% (Figure 3.3). This may be caused by 'shear-yielding': the irreversible slipping of molecular chains; or it may be caused by 'crazing': the formation of low density, crack-like volumes which scatter light, making the polymer look white. Polymers are a little stronger ($\approx$20%) in compression than in tension. Strength, for ceramics and glasses, depends strongly on the mode of loading (Figure 3.4). In tension, 'strength' means the fracture strength, σ_f^t.

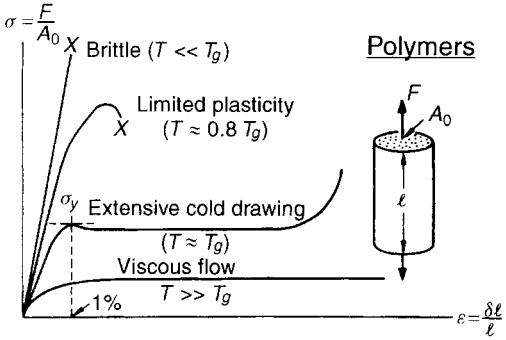

Fig. 3.3 Stress–strain curves for a polymer, below, at and above its glass transition temperature, T_g.

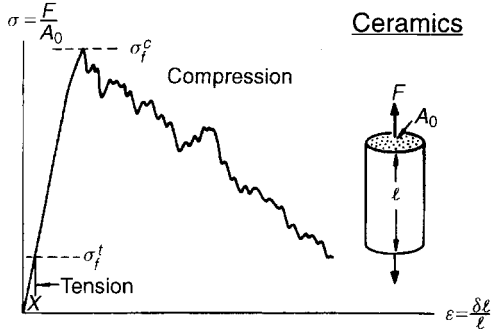

Fig. 3.4 Stress–strain curves for a ceramic in tension and in compression. The compressive strength σ_c is 10 to 15 times greater than the tensile strength σ_t.

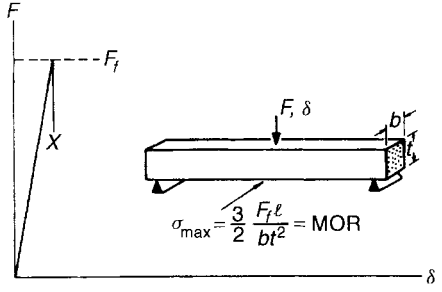

Fig. 3.5 The modulus-of-rupture (MOR) is the surface stress at failure in bending. It is equal to, or slightly larger than the failure stress in tension.

In compression it means the crushing strength σ_f^c which is much larger; typically

$$\sigma_f^c = 10 \text{ to } 15 \times \sigma_f^t \tag{3.3}$$

When the material is difficult to grip (as is a ceramic), its strength can be measured in bending. The *modulus of rupture* or *MOR* (units: MPa or MN/m^2) is the maximum surface stress in a bent beam at the instant of failure (Figure 3.5). One might expect this to be exactly the same as the strength

measured in tension, but for ceramics it is larger (by a factor of about 1.3) because the volume subjected to this maximum stress is small and the probability of a large flaw lying in it is small also; in simple tension all flaws see the maximum stress.

The strength of a composite is best defined by a set deviation from linear-elastic behaviour: 0.5% is sometimes taken. Composites which contain fibres (and this includes natural composites like wood) are a little weaker (up to 30%) in compression than tension because fibres buckle. In subsequent chapters, σ_f for composites means the tensile strength.

Strength, then, depends on material class and on mode of loading. Other modes of loading are possible: shear, for instance. Yield under multiaxial loads are related to that in simple tension by a yield function. For metals, the Von Mises yield function is a good description:

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_f^2 \tag{3.4}$$

where σ_1, σ_2 and σ_3 are the principal stresses, positive when tensile; σ_1, by convention, is the largest or most positive, σ_3 the smallest or least. For polymers the yield function is modified to include the effect of pressure

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_f^2 \left(1 + \frac{\beta p}{K}\right)^2 \tag{3.5}$$

where K is the bulk modulus of the polymer, β (≈ 2) is a numerical coefficient which characterizes the pressure dependence of the flow strength and the pressure p is defined by

$$p = -\frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3)$$

For ceramics, a Coulomb flow law is used:

$$\sigma_1 - B\sigma_3 = C \tag{3.6}$$

where B and C are constants.

The *ultimate (tensile) strength* σ_u (units: MPa) is the nominal stress at which a round bar of the material, loaded in tension, separates (Figure 3.2). For brittle solids — ceramics, glasses and brittle polymers — it is the same as the failure strength in tension. For metals, ductile polymers and most composites, it is larger than the strength σ_f, by a factor of between 1.1 and 3 because of work hardening or (in the case of composites) load transfer to the reinforcement.

The *resilience*, R (units: J/m^3), measures the maximum energy stored elastically without any damage to the material, and which is released again on unloading. It is the area under the elastic part of the stress–strain curve:

$$R = \frac{1}{2}\sigma_f \varepsilon_f = \frac{\sigma_f^2}{2E}$$

where σ_f is the failure load, defined as above, ε_f is the corresponding strain and E is Young's modulus. Materials with large values of R make good springs.

The *hardness*, H, of a material (units: MPa) is a crude measure of its strength. It is measured by pressing a pointed diamond or hardened steel ball into the surface of the material. The hardness is defined as the indenter force divided by the projected area of the indent. It is related to the quantity

we have defined as σ_f by

$$H \cong 3\sigma_f \tag{3.7}$$

Hardness is often measured in other units, the commonest of which is the Vickers H_v scale with units of kg/mm^2. It is related to H in the units used here by

$$H = 10H_v$$

The *toughness*, G_c (units: kJ/m^2), and the *fracture toughness*, K_c (units: MPa m$^{1/2}$ or MN/m$^{1/2}$) measure the resistance of the material to the propagation of a crack. The fracture toughness is measured by loading a sample containing a deliberately introduced crack of length $2c$ (Figure 3.6), recording the tensile stress σ_c at which the crack propagates. The quantity K_c is then calculated from

$$K_c = Y\frac{\sigma_c}{\sqrt{\pi c}} \tag{3.8}$$

and the toughness from

$$G_c = \frac{K_c^2}{E(1+\nu)} \tag{3.9}$$

where Y is a geometric factor, near unity, which depends on details of the sample geometry, E is Young's modulus and ν is Poisson's ratio. Measured in this way K_c and G_c have well-defined values for brittle materials (ceramics, glasses, and many polymers). In ductile materials a plastic zone develops at the crack tip, introducing new features into the way in which cracks propagate which necessitate more involved characterization. Values for K_c and G_c are, nonetheless, cited, and are useful as a way of ranking materials.

The *loss-coefficient*, η (a dimensionless quantity), measures the degree to which a material dissipates vibrational energy (Figure 3.7). If a material is loaded elastically to a stress σ, it stores an elastic energy

$$U = \int_0^{\sigma_{max}} \sigma \, d\varepsilon = \frac{1}{2}\frac{\sigma^2}{E}$$

per unit volume. If it is loaded and then unloaded, it dissipates an energy

$$\Delta U = \oint \sigma \, d\varepsilon$$

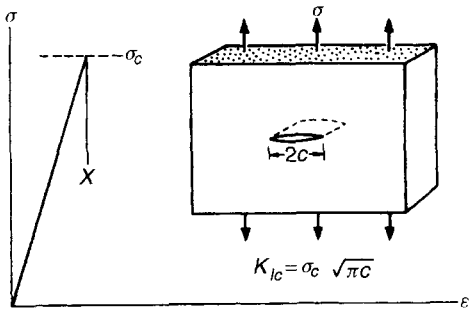

Fig. 3.6 The fracture toughness, K_c, measures the resistance to the propagation of a crack. The failure strength of a brittle solid containing a crack of length $2c$ is $\sigma_f = YK_c\sqrt{\pi c}$ where Y is a constant near unity.

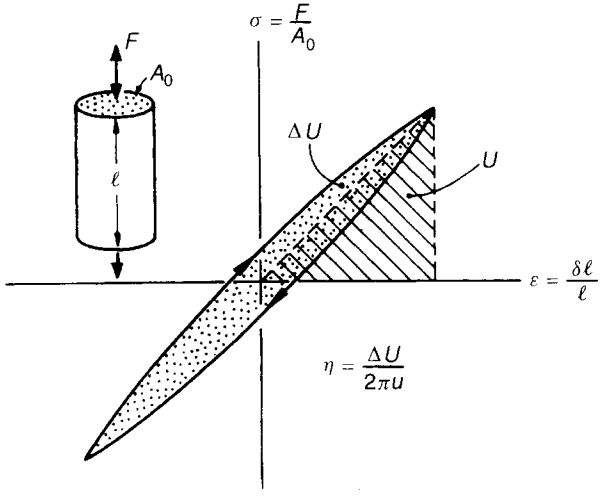

Fig. 3.7 The loss coefficient η measures the fractional energy dissipated in a stress–strain cycle.

The loss coefficient is

$$\eta = \frac{\Delta U}{2\pi U} \tag{3.10}$$

The cycle can be applied in many different ways — some fast, some slow. The value of η usually depends on the timescale or frequency of cycling. Other measures of damping include the *specific damping capacity*, $D = \Delta U/U$, the *log decrement*, Δ (the log of the ratio of successive amplitudes of natural vibrations), the *phase-lag*, δ, between stress and strain, and the *Q-factor* or *resonance factor*, Q. When damping is small ($\eta < 0.01$) these measures are related by

$$\eta = \frac{D}{2\pi} = \frac{\Delta}{\pi} = \tan\delta = \frac{1}{Q} \tag{3.11}$$

but when damping is large, they are no longer equivalent.

Cyclic loading not only dissipates energy; it can also cause a crack to nucleate and grow, culminating in fatigue failure. For many materials there exists a fatigue limit: a stress amplitude below which fracture does not occur, or occurs only after a very large number ($>10^7$) cycles. This information is captured by the *fatigue ratio*, f (a dimensionless quantity). It is the ratio of the fatigue limit to the yield strength, σ_f.

The rate at which heat is conducted through a solid at steady state (meaning that the temperature profile does not change with time) is measured by the *thermal conductivity*, λ (units: W/mK). Figure 3.8 shows how it is measured: by recording the heat flux $q(\mathrm{W/m^2})$ flowing from a surface at temperature T_1 to one at T_2 in the material, separated by a distance X. The conductivity is calculated from Fourier's law:

$$q = -\lambda \frac{\mathrm{d}T}{\mathrm{d}X} = \frac{(T_1 - T_2)}{X} \tag{3.12}$$

The measurement is not, in practice, easy (particularly for materials with low conductivities), but reliable data are now generally available.

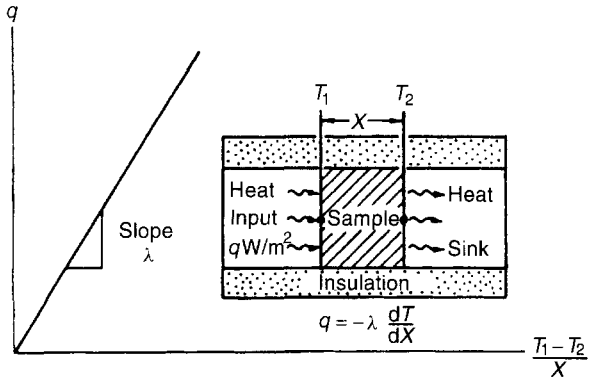

Fig. 3.8 The thermal conductivity λ measures the flux of heat driven by a temperature gradient dT/dX.

When heat flow is transient, the flux depends instead on the *thermal diffusivity*, a (units: m^2/s), defined by

$$a = \frac{\lambda}{\rho C_p} \tag{3.13}$$

where ρ is the density and C_p is the *specific heat at constant pressure* (units: J/kg.K). The thermal diffusivity can be measured directly by measuring the decay of a temperature pulse when a heat source, applied to the material, is switched off; or it can be calculated from λ, via the last equation. This requires values for C_p (virtually identical, for solids, with C_v, the specific heat at constant volume). They are measured by the technique of calorimetry, which is also the standard way of measuring the *melting temperature*, T_m, and the *glass temperature*, T_g (units for both: K). This second temperature is a property of non-crystalline solids, which do not have a sharp melting point; it characterizes the transition from true solid to very viscous liquid. It is helpful, in engineering design, to define two further temperatures: the *maximum service temperature* T_{max} and the *softening temperature*, T_s (both: K). The first tells us the highest temperature at which the material can reasonably be used without oxidation, chemical change or excessive creep becoming a problem; and the second gives the temperature needed to make the material flow easily for forming and shaping.

Most materials expand when they are heated (Figure 3.9). The thermal strain per degree of temperature change is measured by the *linear thermal expansion coefficient*, α (units: K^{-1}). If the material is thermally isotropic, the volume expansion, per degree, is 3α. If it is anisotropic, two or more coefficients are required, and the volume expansion becomes the sum of the principal thermal strains.

The *thermal shock resistance* (units: K) is the maximum temperature difference through which a material can be quenched suddenly without damage. It, and the *creep resistance*, are important in high-temperature design. Creep is the slow, time-dependent deformation which occurs when materials are loaded above about $\frac{1}{3}T_m$ or $\frac{2}{3}T_g$ (Figure 3.10). It is characterized by a set of *creep constants:* a creep exponent n (dimensionless), an activation energy Q (units: kJ/mole), a kinetic factor $\dot{\varepsilon}_0$ (units: s^{-1}), and a reference stress σ_0 (units: MPa or MN/m^2). The creep strain-rate $\dot{\varepsilon}$ at a temperature T caused by a stress σ is described by the equation

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \left(\frac{\sigma}{\sigma_0}\right)^n \exp - \left(\frac{Q}{RT}\right) \tag{3.14}$$

where R is the gas constant (8.314 J/mol K).

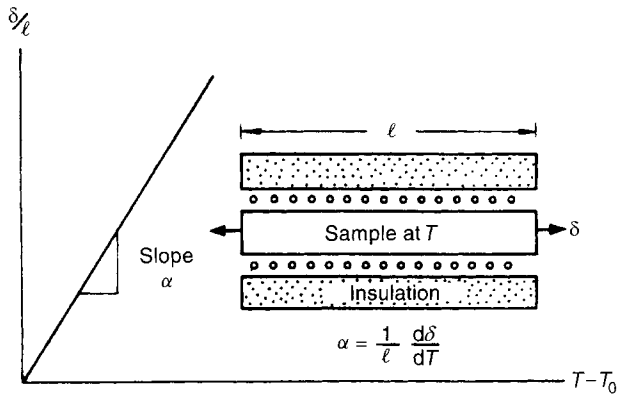

Fig. 3.9 The linear-thermal expansion coefficient α measures the change in length, per unit length, when the sample is heated.

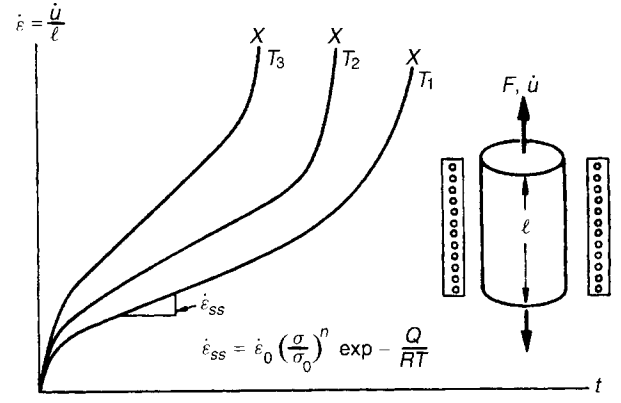

Fig. 3.10 Creep is the slow deformation with time under load. It is characterized by the creep constants, $\dot{\varepsilon}_0$, σ_0 and Q.

Wear, oxidation and corrosion are harder to quantify, partly because they are surface, not bulk, phenomena, and partly because they involve interactions between two materials, not just the properties of one. When solids slide (Figure 3.11) the volume of material lost from one surface, per unit distance slid, is called the wear rate, W. The wear resistance of the surface is characterized by the *Archard wear constant*, k_A (units: m/MN or MPa), defined by the equation

$$\frac{W}{A} = k_A P \tag{3.15}$$

where A is the area of the surface and P the pressure (i.e. force per unit area) pressing them together. Data for k_A are available, but must be interpreted as the property of the sliding couple, not of just one member of it.

Dry corrosion is the chemical reaction of a solid surface with dry gases (Figure 3.12). Typically, a metal, M, reacts with oxygen, O_2, to give a surface layer of the oxide MO_2:

$$M + O_2 = MO_2$$

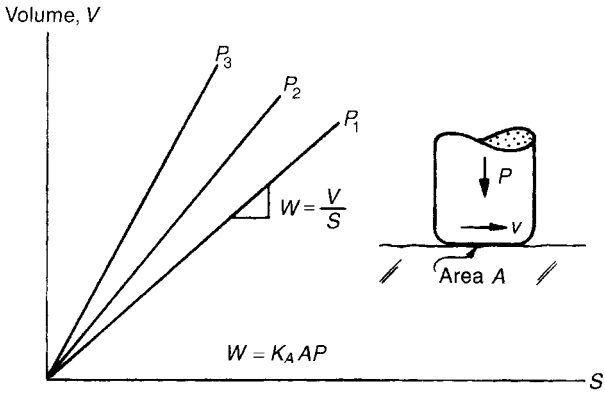

Fig. 3.11 Wear is the loss of material from surfaces when they slide. The wear resistance is measured by the Archard wear constant K_A.

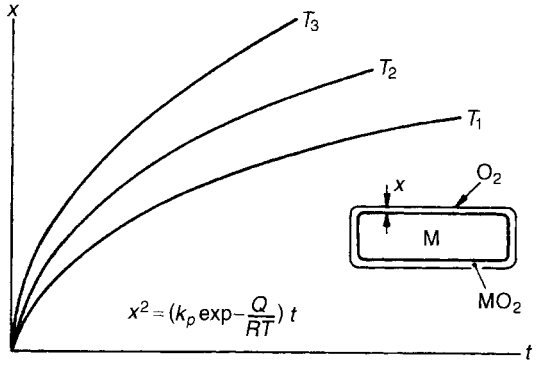

Fig. 3.12 Corrosion is the surface reaction of the material with gases or liquids — usually aqueous solutions. Sometimes it can be described by a simple rate equation, but usually the process is too complicated to allow this.

If the oxide is protective, forming a continuous, uncracked film (thickness x) over the surface, the reaction slows down with time t:

$$\frac{dx}{dt} = \frac{k_p}{x}\left\{\exp - \left(\frac{Q}{RT}\right)\right\} \tag{3.16}$$

or, on integrating,

$$x^2 = k_p\left\{\exp - \left(\frac{Q}{RT}\right)\right\} t$$

Here R is the gas constant, T the absolute temperature, and the oxidation behaviour is characterized by the *parabolic rate constant for oxidation* k_p (units: m^2/s) and an activation energy Q (units: kJ/mole).

Wet corrosion — corrosion in water, brine, acids or alkalis — is much more complicated and cannot be captured by rate equations with simple constants. It is more usual to catalogue corrosion resistance by a simple scale such as A (very good) to E (very bad).

3.4 Summary and conclusions

There are six important classes of materials for mechanical design: metals, polymers elastomers, ceramics, glasses, and composites which combine the properties of two or more of the others. Within a class there is certain common ground: ceramics as a class are hard, brittle and corrosion resistant; metals as a class are ductile, tough and electrical conductors; polymers as a class are light, easily shaped and electrical insulators, and so on — that is what makes the classification useful. But, in design, we wish to escape from the constraints of class, and think, instead, of the material name as an identifier for a certain property-profile — one which will, in later chapters, be compared with an 'ideal' profile suggested by the design, guiding our choice. To that end, the properties important in thermo-mechanical design were defined in this chapter. In the next we develop a way of displaying properties so as to maximize the freedom of choice.

3.5 Further reading

Definitions of material properties can be found in numerous general texts on engineering materials, among them those listed here.

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